

STABILITY OF EARTH-MASS PLANETS IN THE KEPLER-68 SYSTEM

STEPHEN R. KANE

Department of Physics & Astronomy, San Francisco State University, 1600 Holloway Avenue, San Francisco, CA 94132, USA
Submitted for publication in the Astrophysical Journal Letters

ABSTRACT

A key component of characterizing multi-planet exosystems is testing the orbital stability based on the observed properties. Such characterization not only tests the validity of how observations are interpreted but can also place additional constraints upon the properties of the detected planets. The *Kepler* mission has identified hundreds of multi-planet systems but there are a few that have additional non-transiting planets and also have well characterized host stars. Kepler-68 is one such system for which we are able to provide a detailed study of the orbital dynamics. We use the stellar parameters to calculate the extent of the Habitable Zone for this system, showing that the outer planet lies within that region. We use N-body integrations to study the orbital stability of the system, in particular placing an orbital inclination constraint on the outer planet of $i > 5^\circ$. Finally, we present the results of an exhaustive stability simulation that investigates possible locations of stable orbits for an Earth-mass planet. We show that there are several islands of stability within the Habitable Zone that could harbor such a planet, most particularly at the 2:3 mean motion resonance with the outer planet.

Subject headings: astrobiology – planetary systems – stars: individual (Kepler-68)

1. INTRODUCTION

The characterization of exoplanetary systems and their host stars is an ongoing effort, often requiring substantial telescope time. This is particularly true of the exoplanet candidates from the *Kepler* mission (Borucki et al. 2011a,b; Batalha et al. 2013; Burke et al. 2014; Rowe et al. 2015), for which validation of the candidates with relatively faint host stars and/or small planets can be challenging. Fortunately, multiplicity in an exoplanet system reveals that it has an exceptionally low probability of being a false-alarm, allowing many of the multi-planet Kepler systems to be validated (Lissauer et al. 2014; Rowe et al. 2014). Additional characterization of such systems includes testing orbital stability for those in which the planetary masses can be determined, either through measurable Transit Timing Variations (TTVs) or radial velocity (RV) effects (Li et al. 2014; Mahajan & Wu 2014).

An additional aspect that can be tested for multi-planet systems is the possible locations of dynamical stability for terrestrial planets within the star's Habitable Zone (HZ). Examples of stability studies include predicting planets in known exosystems (Barnes & Raymond 2004; Raymond & Barnes 2005; Raymond et al. 2006) as well as studies of individual systems such as HD 47186 (Kopparapu et al. 2009), 70 Vir (Kane et al. 2015), and numerous other systems (Menou & Tabachnik 2003; Kopparapu & Barnes 2010). These studies require a well characterized host star that allows accurate HZ calculations to be performed. One such confirmed Kepler system is that of Kepler-68, published by Gilliland et al. (2013). Kepler-68 is relatively bright, making it suitable for RV follow-up and astroseismology studies. These have been used to great effect resulting not only in well-determined fundamental properties of the host star, but also the detection of a non-transiting giant planet, bring-

ing the total number of known planets in the system to three. This introduces a fascinating system that deserves further study into the dynamical limitations imposed by the known orbits.

Here we present the results of an exhaustive stability analysis of the Kepler-68 system along with HZ calculations and constraints on the presence of an Earth-mass planet in the HZ. Section 2 discusses the known stellar and planetary parameters of the system and uses these to calculate the system HZ. Section 3 describes the orbital stability of the system and shows the results of varying the inclination of the outer non-transiting planet. Section 4 combines the methodology of the previous two sections by inserting a hypothetical Earth-mass planet at a large range of semi-major axes and locating the islands of stability that may exist with respect to the HZ. We provide concluding remarks and discussion of future work in Section 5.

2. SYSTEM PARAMETERS AND HABITABLE ZONE

The Kepler-68 (KOI-246; KIC 11295426) system was originally identified in the first release of Kepler candidates (Borucki et al. 2011a,b). The star was found to harbor two transiting planets, labeled 'b' and 'c', with orbital periods of 5.399 and 9.605 days respectively. The brightness of Kepler-68 ($K_p = 10$) enabled precise RV measurements that revealed the presence of a third ('d') non-transiting planet in an eccentric orbit ($e = 0.18$) with an orbital period of ~ 580 days (Gilliland et al. 2013). The combination of spectroscopic and astroseismic modeling were used to determine stellar properties of $T_{\text{eff}} = 5793 \pm 74$ K, $M_\star = 1.079 \pm 0.051 M_\odot$, $R_\star = 1.243 \pm 0.019 R_\odot$, and $L_\star = 1.564 \pm 0.141 L_\odot$. The resulting semi-major axes of planets b, c, and d are thus 0.061, 0.091, and 1.4 AU respectively and their masses are $8.3 M_\oplus$, $4.8 M_\oplus$, and $0.947 M_J$ respectively. Full details of the stellar and planetary properties of the system may be found in Gilliland et al. (2013).

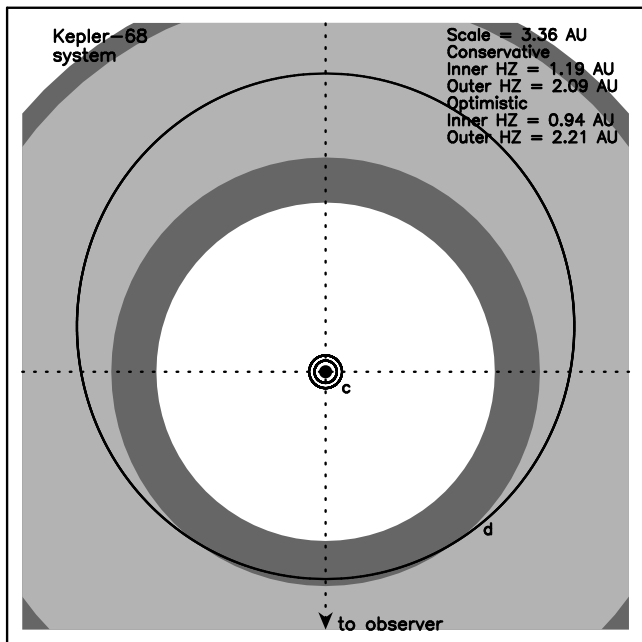


FIG. 1.— A top-down view of the Kepler-68 system showing the extent of the HZ and orbits of the planets calculated using the stellar and planetary parameters from Gilliland et al. (2013). The physical scale depicted is 3.36 AU on a side. The conservative HZ is shown as light-gray and optimistic extension to the HZ is shown as dark-gray. The inner-most (unlabeled) orbit is that of planet b.

Using the stellar properties described above, we calculate the boundaries of the HZ as described by Kopparapu et al. (2013, 2014). We further use the terms “conservative” and “optimistic” (see Kane et al. (2013)) to label HZ regions that are based on assumptions regarding the amount of time that Venus and Mars were able to retain liquid water on their surfaces (Kopparapu et al. 2013). The uncertainties in HZ boundaries were demonstrated by Kane (2014) to be largely impacted by the stellar radius and subsequent luminosity uncertainties. Fortunately the stellar parameters for Kepler-68 are known sufficiently well from astroseismology measurements such that the HZ boundary uncertainties are negligibly small. For further information on HZ calculations for all known exoplanetary systems using the above described methodology, we refer the reader to the Habitable Zone Gallery (Kane & Gelino 2012).

The calculated HZ boundaries for the Kepler-68 system are depicted in Figure 1, along with the orbits of the three known planets. The conservative HZ is shown as light-gray with inner and outer boundaries located at 1.19 and 2.09 AU respectively. The optimistic extension to the HZ is shown as dark-gray with inner and outer boundaries of 0.94 and 2.21 AU respectively. A key aspect to notice in Figure 1 is that the measured orbit of the d planet spans a wide range of star-planet separations throughout the HZ due to the orbital eccentricity of the planet. It will therefore be significant to determine if such an orbit excludes the presence of Earth-mass planets in the HZ.

3. ORBITAL STABILITY AND INCLINATION OF OUTER PLANET

Considering the known planets in the Kepler-68 system include two very close-in planets of moderate mass and a giant eccentric planet of unknown orbital inclination, it

is useful to test stability scenarios. To do this, we calculated dynamical simulations using N-body integrations with the Mercury Integrator Package, described in more detail by Chambers (1999). Our simulations made use of the hybrid symplectic/Bulirsch-Stoer integrator and a Jacobi coordinate system, since this coordinate system generally provides more accurate results for multi-planet systems (Wisdom & Holman 1991; Wisdom 2006) except in cases of close encounters (Chambers 1999). All of the integrations were performed for a simulation duration of 10^6 years starting at the present epoch, with results output in steps of 100 years. Occasional checks using 10^7 year simulations were used to verify that instability regions beyond the 10^6 timescale were not being missed. We used a time resolution of 0.25 days to meet the recommended requirement of choosing a timestep $1/20$ of the shortest orbital period (Duncan et al. 1998), ~ 5.4 days in this case. A single simulation of the system assuming that the system is approximately coplanar ($i = 90^\circ$ for planet d) showed that the system is indeed stable over long timescales for such a configuration.

To test the effect of planet d inclination, we performed a sequence of stability simulations that vary the orbital inclination of the outer planet from edge-on ($i = 90^\circ$) to face-on ($i = 0^\circ$) in steps of 1° . Since the true mass of the outer planet is the measured mass divided by $\sin i$, the mass of the outer planet in the simulations is adjusted accordingly. The stability simulations show that the system remains stable throughout the full duration of the simulation for all inclinations of planet d in the range $90^\circ \leq i \leq 5^\circ$. For inclinations less than 5° , the orbits of the inner planets become significantly perturbed by planet d such that the system stability is compromised. To increase the inclination resolution in this region, we performed a further set of stability simulations from 5° to 0° in steps of 0.05° . The survival of the inner planets as a function of planet d’s orbital inclination is shown in the top panel of Figure 2. The system is clearly catastrophically unstable within this range, where the seemingly chaotic survival times are due to the sensitivity of the simulations to initial starting conditions.

The range of true masses for planet d in the inclination range 5° – 0° is 0.01–0.5 solar masses, shown as a solid line in Figure 2. Inclinations less than 1° move the mass of the d component into the stellar regime. In addition to the instability reasons, it is highly unlikely that the d component is stellar in nature due to the expected evidence from follow-up observations. The BLENDER analysis developed by Torres et al. (2011) and used by Gilliland et al. (2013) did not indicate a centroid shift that is characteristic of a false-positive, nor did the acquired spectra show signs of lines shifts due to a stellar companion.

The bottom panel of Figure 2 shows the change in eccentricities of planets b and c as a function of time for the case where planet d’s inclination is 4.55° . This is shown as an example of the orbital degradation that occurs at the threshold of instability. The inner planets oscillate with the same frequency until planet c is removed from the system at a time of $\sim 170,000$ years, after which planet b survives until $\sim 280,000$ years. To be clear, the removal of planets in this context does not mean that they are ejected from the system. The inner planets are unlikely to be able to escape the gravitational potential

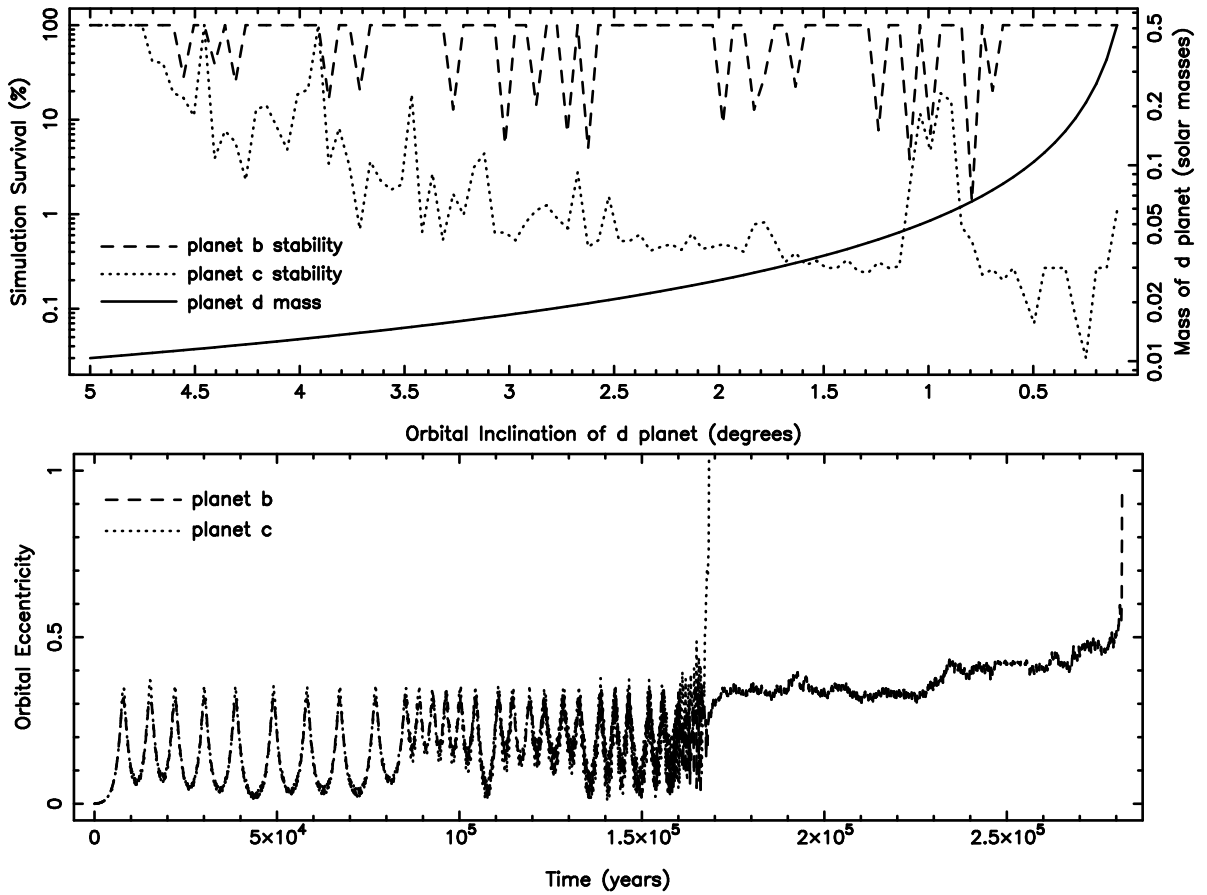


FIG. 2.— Top: The percentage simulation survival of the two inner planets as a function of orbital inclination of planet d. The survival of planets b and c are shown as dashed and dotted lines respectively. Also shown is a solid line that represents the increasing true mass of planet d as the orbital inclination moves toward being face-on, with the mass values shown on the right-hand axis. Bottom: The orbital eccentricities of planets b and c as a function of time for a planet d orbital inclination of 4.55° . The eccentricities of planets b and c are depicted as dashed and dotted lines respectively. The eccentricities of the two inner planets oscillate in identical ways until planet c is lost after $\sim 170,000$ years. Planet b then survives in the system until $\sim 280,000$ years.

well of the host star and so the planets will be consumed by the star rather than ejected. Since the radius of star is 0.0058 AU, the eccentricities for which this will occur for planets b and c are 0.90 and 0.94 respectively.

We have shown that the inclination of the outer planet has to be unrealistically small in order to render the system unstable. Indeed most of the Kepler systems have been found to be consistent with the prevalence of coplanarity amongst multi-planet systems (Fang & Margot 2012). A consequence of this is that there are large stability regions that exist within the system as possible locations for further planets, as investigated in the next section.

4. CONSTRAINTS ON THE PRESENCE OF AN EARTH-MASS PLANET

As noted earlier, the stellar properties of the Kepler-68 host star are relatively well defined. This presents an opportunity to examine the possibility that other terrestrial planets may exist in the system beneath the detection limits of current data. To test the viability of such a scenario, we conducted an exhaustive set of simulations that place an Earth-mass planet with a circular orbit at various locations within the system. We assumed that the planetary orbits are approximately coplanar including the known outermost planet d.

Using the system configuration described above, we performed 1,000 simulations that increment the semi-major axis of the simulated planet between 0.1 and 3.0 AU. The inner boundary of 0.1 AU was chosen to lie just beyond the location of planet c. Each simulation had a duration of 10^6 years, as described in Section 3. Shown in Figure 3 are the results of the simulation, where the percentage of the simulation that the inserted planet remained in the system is plotted against the semi-major axis of the planet. The light-gray and dark-gray regions represent the conservative and optimistic HZ regions respectively.

Given that planet d has an eccentricity of $e = 0.18$ and a semi-major axis $a = 1.4$, it is not surprising that there are vast swathes of instability that lie throughout the HZ. The periastron and apastron distances of planet d are 1.15 and 1.65 AU respectively. The mass of the planet yields a Hill radius of ~ 0.1 AU, consistent with the boundaries of the instability regions seen in Figure 3 (Marchal & Bozis 1982; Gladman 1993). The vertical dashed lines show the locations of the mean motion orbital resonances (MMR) with planet d. As described by Raymond et al. (2008), some MMR locations are preferred to others and indeed there are MMR locations that are destabilizing regions (such as the 1:2 MMR)

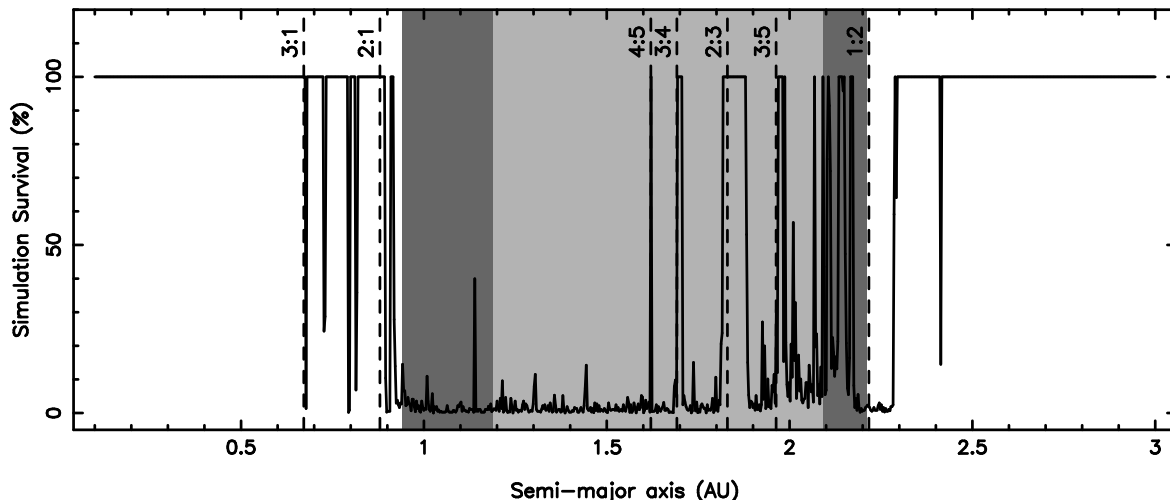


FIG. 3.— The orbital stability of a hypothetical Earth-mass planet as a function of semi-major axis in the Kepler-68 system. The orbital stability on the vertical axis is expressed as the percentage simulation survival for each semi-major axis where the position of the planet was tested. The system is assumed to be coplanar and the orbit of the Earth-mass is assumed to be circular. The light-gray and dark-gray regions represent the conservative and optimistic HZ regions, as per Figure 1. The vertical dashed lines indicate the locations of the mean-motion orbital resonances with planet d.

rather than locations for MMR trapping. Although it seems that the presence of planet d excludes the possibility of a terrestrial planet in the Kepler-68 HZ, there lies an extended region of stability within 1.8–1.9 AU that corresponds to the 2:3 MMR location. This island of stability lies well within the conservative HZ for the system. For an Earth-mass planet, the RV amplitude within the stability island would be $\sim 6 \text{ cm s}^{-1}$, beyond the reach of current instruments for a star so faint. Furthermore, an Earth-radius planet would have a transit depth of $\sim 55 \text{ ppm}$ with an orbital period of ~ 880 days at 1.85 AU. Such a signature would occur at most twice within the *Kepler* time series, presenting significant detectability challenges.

5. CONCLUSIONS

The necessity of follow-up for Kepler candidates is clearly vital for both confirming their planetary status as well as understanding the host stars. Kepler-68 is one of the few cases where non-transiting planets have been discovered through such follow-up activities, revealing an intriguing system with an eccentric giant planet (planet d). We have calculated the HZ for this system and have shown that the d planet carves a path right through the HZ.

When non-transiting planets are found, it lays open the subject of how the system stability depends on the inclination of such planets. To resolve this issue, we have conducted extensive N-body stability simulations that show the system is stable for all inclinations of the d planet from 90° to $\sim 5^\circ$. The d planet begins to adopt stellar properties for inclinations less than 1° which reinforces the exclusion of such inclinations since the companions would undoubtedly have been detected in the follow-up data described by Gilliland et al. (2013).

We further investigated the locations within the system where a terrestrial planet of one Earth-mass could potentially maintain a stable orbit. We showed how planet d is a particularly destabilizing factor within the system HZ, apart from an island of stability between 1.8–1.9 AU and various other narrow locations where MMR trapping can occur. There are many locations outside of the HZ where such a hypothetical planet could be harbored without risk of gravitational encounters that would render its continued orbit untenable. The other reason that the presence of the giant planet is not necessarily a deterrent to habitability is because such a planet could harbor terrestrial moons that may themselves be habitable (Forgan & Kipping 2013; Hinkel & Kane 2013; Heller et al. 2014). However, the frequency of giant planets within the HZ is clearly a topic that cannot be ignored in subsequent searches for terrestrial HZ planets.

ACKNOWLEDGEMENTS

The author would like to thank Gregory Laughlin and Sean Raymond for useful discussions on the stability simulations. Thanks are also due to Ronald Gilliland and the anonymous referee, whose feedback improved the quality of the paper. This research has made use of the following archives: the Exoplanet Orbit Database and the Exoplanet Data Explorer at exoplanets.org, the Habitable Zone Gallery at hzgallery.org, and the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. The results reported herein benefited from collaborations and/or information exchange within NASA’s Nexus for Exoplanet System Science (NExSS) research coordination network sponsored by NASA’s Science Mission Directorate.

REFERENCES

- Barnes, R., Raymond, S.N. 2004, *ApJ*, 617, 569
 Batalha, N.M., Rowe, J.F., Bryson, S.T., et al. 2013, *ApJS*, 204, 24
 Borucki, W.J., Koch, D.G., Basri, G., et al. 2011a, *ApJ*, 728, 117
 Borucki, W.J., Koch, D.G., Basri, G., et al. 2011b, *ApJ*, 736, 19
 Burke, C.J., Bryson, S.T., Mullally, F., et al. 2014, *ApJS*, 210, 19

- Chambers, J.E. 1999, MNRAS, 304, 793
Duncan, M.J., Levison, H.F., Lee, M.H. 1998, AJ, 116, 2067
Fang, J., Margot, J.-L. 2012, ApJ, 761, 92
Forgan, D., Kipping, D. 2013, MNRAS, 432, 2994
Gilliland, R.L., Marcy, G.W., Rowe, J.F., et al. 2013, ApJ, 766, 40
Gladman, B. 1993, Icarus, 106, 247
Heller, R., Williams, D., Kipping, D., et al. 2014, AsBio, 14, 798
Hinkel, N.R., Kane, S.R. 2013, ApJ, 774, 27
Kane, S.R., Gelino, D.M. 2012, PASP, 124, 323
Kane, S.R., Barclay, T., Gelino, D.M. 2013, ApJ, 770, L20
Kane, S.R. 2014, ApJ, 782, 111
Kane, S.R., Boyajian, T.S., Henry, G.W., et al. 2015, ApJ, 806, 60
Kopparapu, R.K., Raymond, S.N., Barnes, R. 2009, ApJ, 695, L181
Kopparapu, R.K., Barnes, R. 2010, ApJ, 716, 1336
Kopparapu, R.K., Ramirez, R., Kasting, J.F., et al. 2013, ApJ, 765, 131
Kopparapu, R.K., Ramirez, R.M., SchottelKotte, J., et al. 2014, ApJ, 787, L29
Li, G., Naoz, S., Valsecchi, F., Johnson, J.A., Rasio, F.A. 2014, ApJ, 794, 131
Lissauer, J.J., Marcy, G.W., Bryson, S.T., et al., 2014, ApJ, 784, 44
Mahajan, N., Wu, Y. 2014, ApJ, 795, 32
Marchal, C., Bozis, G. 1982, CeMec, 26, 311
Menou, K., Tabachnik, S. 2003, ApJ, 583, 473
Raymond, S.N., Barnes, R. 2005, ApJ, 619, 549
Raymond, S.N., Barnes, R., Kaib, N.A. 2006, ApJ, 644, 1223
Raymond, S.N., Barnes, R., Armitage, P.J., Gorelick, N. 2008, ApJ, 687, L107
Rowe, J.F., Bryson, S.T., Marcy, G.W., et al., 2014, ApJ, 784, 45
Rowe, J.F., Coughlin, J.L., Antoci, V., et al., 2015, ApJS, 217, 16
Torres, G., Fressin, F., Batalha, N.M., et al. 2011, ApJ, 727, 24
Wisdom, J., Holman, M. 1991, AJ, 102, 1528
Wisdom, J. 2006, AJ, 131, 2294